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Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Attention: Mr. Jeffrey A. Ciocco,

Project No.0751
MHI Ref: UAP-HF-07057

Subject: US-APWR M-RELAP5 Code Validation Plan (Preliminary)

This letter transmits to the U.S. Nuclear Regulatory Commission (NRC) the preliminary validation plan for the M-RELAP5 code, which will be used for the US-APWR small break LOCA analysis. As discussed in the sixth pre-application review meeting for the US-APWR between MHI and the NRC staff on March 22, 2007, MHI would like to obtain the staff's review and comment on the validation plan in advance of submitting the topical report on small break LOCA methodology.

The enclosure consists of the preliminary validation plan and a Phenomena Identification and Ranking Table (PIRT) as an appendix to the plan. The PIRT explains the selection of the tests for the validation plan.

Please contact Dr. C. Keith Paulson, Senior Technical Manager, Mitsubishi Nuclear Energy Systems, Inc. if there are questions regarding this matter. His contact information is listed below.

Sincerely,

M. Kaneda

Masahiko Kaneda,
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Enclosure: US-APWR M-RELAP5 Code Validation Plan (Preliminary)

CC: Mr. Steve. R. Monarque, TXU New Plant Project Manager, NRC
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Enclosure

US-APWR M-RELAP5 Code Validation Plan (Preliminary)

UAP-HF-07057

US-APWR

M-RELAP5 Code Validation Plan

(Preliminary)

June 2007

MITSUBISHI HEAVY INDUSTRIES, LTD.

1. INTRODUCTION

This document describes a plan to validate the M-RELAP5 code that will be used for the US-APWR small break LOCA analysis.

2. VALIDATION PLAN

2.1 PIRT

To validate M-RELAP5, which is a modified version of RELAP5-3D, MHI has developed a Phenomena Identification and Ranking Table (PIRT) for Small Break LOCA of the US-APWR. The preliminary PIRT is attached as an Appendix to this plan. The phenomena that are ranked as High in this PIRT are shown in Table-1. The final PIRT will be part of the topical report on "Small Beak LOCA methodology".

2.2 Validation plan

For the phenomena ranked as High in table-1, the phenomena are either modeled conservatively based on the Appendix-K requirements or will be confirmed by the test calculations.

2.2.1 Modeling based on Appendix-K requirements

The phenomena that will be modeled conservatively based on the Appendix-K requirements are the followings:

- Decay heat: ANS-1971 x 1.2 decay heat curve will be used.
- Local power of fuel rod: Highest peaking power will be used.
- 3-D power distribution of core: Highest peaking power will be used.
- Safety Injection flow rate: Most limiting single failure will be assumed.
- Critical flow: Moody's critical flow model will be used.

2.2.2 Confirmation plan

The following validation plan has been developed to confirm, as shown in table-2, the other phenomena ranked as High.

(1) Core mixture level related models

The core mixture level related models will be confirmed using the following tests results:

- ORNL/THTF Void Profile test
  Core dryout, Post-CHF heat transfer and core mixture level will be confirmed.
- ROSA/LSTF Void Profile test
  Core mixture level will be confirmed.
- ORNL/THTF Uncovered heat transfer test
  Core dryout and Post-CHF heat transfer will be confirmed.
- ORNL/THTF Reflood test
  Post-CHF heat transfer and Rewet (heat transfer recovery) will be confirmed.

(2) SG primary side CCFL model

The CCFL model will be confirmed by comparing the calculated values to the following test results:

- UPTF SG plenum CCFL test (Kutateladze type correlation)
  Water hold-up in SG plenum will be confirmed.
- Dukler Air-Water Flooding test (Wallis type correlation)
  Water hold-up in U-tube uphill side will be confirmed.

(3) Integral test results

The calculated results by M-RELAP5 will be compared with Small Break LOCA integral tests:

- ROSA-IV/LSTF small break (5%) LOCA test (SB-CL-18)
- Semiscale Mod-2C small-break (5%) LOCA tests S-LH-1 (0.9% bypass)

Using the integral test calculation, integral system behavior as well as the following phenomena will be confirmed: core dryout, Post-CHF heat transfer, rewet, core mixture level, water hold up in SG primary side, condensation drainage to inlet plenum, SG primary and secondary heat transfer, water level in SG outlet piping, loop seal formation and clearance, downcomer mixture level.

Table-1 PIRT for Small Break LOCA (High rank)

Location	Process / Phenomena	Small Break LOCA Blowdown	Natural Circulation	Loop Seal Clearance	Boil-off	Recovery
FUEL ROD						
3	Decay Heat	M	M	H	H	H
7	Local Power	L	L	H*	H	H
CORE						
9	Dryout	N/A	N/A	H	H	H
10	Post-CHF Heat Transfer	N/A	N/A	H	H	H
11	Rewet (Heat Transfer Recovery)	N/A	N/A	H	H	H
14	Mixture Level	N/A	N/A	H	H	H
16	3-D Power Distribution	L	L	H	H	H
Steam Generator						
37	Water Hold-Up in SG Plenum	L	L	H	L	L
38	Water Hold-Up in U-Tube Uphill Side	L	L	H	L	L
39	Condensate drainage to inlet plenum	L	L	H	M*	L
40	Primary Side Heat Transfer	M	M	H	M*	L
Crossover Leg						
45	Water level in SG outlet piping	L	L	H	L	L
46	Loop Seal formation and Clearance (Entrainment/Flow regime/Interfacial drag/Flow resistance)	L	L	H	M	L
Downcomer/Lower Plenum						
62	Mixture Level	M	M	H	H	H
66	DVI/SI Water / Flowrate	N/A	M	H	H	H
Break						
69	Critical Flow	H	H	H	H	H

H = The process is considered to have high importance.
M = The process is considered to have medium importance.
L = The process is considered to have low importance.
N/A = The process is considered not to occur at all.
* means that the ranking is break size dependent.

Table-2 Validation Tests for High Ranking Phenomena for Small Break LOCA

	Core Dryout	Post-CHF heat transfer	Rewet	Core mixture level	Water hold-up in SG plenum	Water hold-up in U-tube uphill side	Condensation drainage to inlet plenum	SG primary and secondary heat transfer	Water level in SG outlet piping	Loop seal formation and clearance	Downcomer mixture level
ORNL/THTF Void Profile test	X	X		X							
ROSA/LSTF Void Profile test				X							
ORNL/THTF Uncovered heat transfer test	X	X									
ORNL/THTF Reflood test		X	X								
UPTF SG plenum CCFL test					X						
Dukler Air-Water Flooding test						X					
ROSA-IV/LSTF small break (5%) LOCA test	X	X	X	X	X	X	X	X	X	X	X
Semiscale small-break (5%) LOCA tests S-LH-1	X	X	X	X	X	X	X	X	X	X	X

Appendix Small Break LOCA PIRT

1.0 INTRODUCTION

One of the most important steps in developing an analysis methodology is identification of phenomena and processes which provide the most dominant influence on the subject transients. Phenomena Identification and Ranking Table (PIRT) lists key processes and specifies at which transient period the process occurs. The PIRT developed for small break Loss-of-Coolant Accident (LOCA) in Mitsubishi US-APWR is described. Phenomenon is identified by major components, and a ranking is assigned for the respective periods of small break LOCA. Since the PIRT depends on a plant and its associated scenario, the overview of the US-APWR plant and its small LOCA transient is described below in sections 1-1 and 1-2.

2.0 Target Plant / US-APWR

This PIRT applies to those phenomena and processes that would occur in Mitsubishi US-APWR small break LOCA transients. US-APWR is a four-loop type PWR, in which high pressure safety injection pumps perform safety injection directly to the downcomer (Direct Vessel Injection (DVI)) and advanced accumulators inject to the cold legs. It is assumed that the plant is in its normal, full power operation mode in accordance with its Technical Specifications at the time of small break LOCA occurrence.

3.0 Accident Scenario

The assumed accident is a small break LOCA with a most limiting single failure associated with the safeguard system. A cold leg break is assumed as the limiting break location in view of core cooling.

During a small break LOCA transient, a reactor trip signal is generated when the RCS depressurizes to the “pressurizer low-pressure” set point. The US-APWR design employs a four–train direct vessel injection (DVI) system, and it is activated by an S-signal which is generated when the RCS depressurizes to “pressurizer low-low pressure” set point. The accumulator system consists of four advanced accumulators and the associated valves and piping, one for each cold leg. The system injects borated water when the RCS pressure falls below the accumulator operating pressure.

During a small break LOCA, the reactor vessel depressurizes and the reactor vessel mass inventory is lost out the break as the RCS drains to the break while the DVI and accumulator systems add liquid mass to the RCS. Quantity of the injected water must be sufficient so that the core is cooled down to an acceptable degree for the spectrum of small break LOCA transients.

4.0 Small Break LOCA Scenario

In order to identify various phenomena and provide ranking to them, it is useful to divide the small break LOCA transient into several phases. Some phenomena, which exhibit a significant importance in a certain period, may not necessarily exhibit such significance in other period. However, simulation of a certain phenomenon for a period important with respect to the phenomenon might play a crucial role in determining the accuracy of the whole transient simulation. Small break LOCA transients can be divided and characterized by five time periods: Blowdown, Natural Circulation, Loop Seal Clearance, Boil-off and Core Recovery. The length of each time period depends on the break size. Each is characterized as follows:

Blowdown (BLD):
Upon initiation of the break, the RCS primary side rapidly depressurizes until flashing of the hot coolant into steam is started. Reactor trip is initiated on "pressurizer pressure low" set point. Loss of condenser steam dump isolates the SG secondary side. As a result, The SG secondary side pressure rises to the safety valve set point, and the steam is released through the safety valves. A safety injection signal is generated at the time that the pressurizer pressure decreases to "pressurizer low-low" set point, and the safety injection initiate after a certain delayed time. The RCS stays in liquid phase in most of the blowdown period, although towards the end of the period, phase separation occurs in the upper head, upper plenum and hot legs. The break flow is in liquid phase throughout the blowdown period. Then eventually the entire RCS becomes saturated, the rapid depressurization terminates, and the RCS pressure reaches adjacent to the secondary side of SG pressure.

Natural Circulation (NC):
When the blowdown period ends, RCS pressure settles slightly above the SG secondary side pressure because the core decay heat remains removed by steam condensation in the SG tubes. Pressure rise in the secondary side is prevented by frequent steam venting and an auxiliary feedwater flow is initiated to maintain the secondary side liquid inventory. During this period, sufficient coolant exists in the RCS, and natural circulation by two-phase flow is established. By the continued loss of coolant from the RCS some vapor carried into the SG tubes remains uncondensed and creates a continuous vapor phase at the downhill side of the tubes and the crossover leg. This terminates the natural circulation.

Loop Seal Clearance (LSC):
The third period is the loop seal clearance period. When the liquid level in the downhill side of the crossover leg is depressed and reaches the bottom of the loop seal, steam in the RCS is vented to the cold leg. The break flow changes from low quality mixture to primarily steam. Prior to the loop seal clearance, the core collapsed level can reduce as a result of static water head balancing within the RCS. More specifically the core level depletion is affected by the water head at the pump suction and the uphill side of SG. After the loop seal clearance, the water level in the reactor vessel recovers to the cold leg elevation as the steam venting dissolves the water head imbalance throughout the RCS.
If the mixture core level drops to the core top and core uncovery initiates, the cladding temperature in the upper part of the core may begin to rise rapidly. The temperature rise is not so remarkable because the temperature excursions will be stopped by returning mixture level in a short period.

Boil-off (BO):
After the loop seal clears, the primary pressure falls below that of the secondary side due to the increase of the break flow quality. This changes the direction of heat transfer in the SG so that the secondary side begins to supply heat to the primary side.
For the medium break size, the vessel mixture level may decrease as a result of the core boiling-off. This is generally because the RCS pressure is too high for the injection system to provide sufficient injection to the RCS. For the US-APWR the safety injection pump is designed to provide with the coolant corresponding to the boiling-off flow with one train in case of the DVI line (3.4-inch inner diameter) guillotine break. This allows the vessel mixture level to be kept in case a cold leg break within the scale corresponding to twice of the DVI line. For the larger break cases, the core might be uncovered before the RCS depressurizes to the point

where the safety injection pumps and accumulators deliver ECC water to the RCS at a higher rate than the break flow.

Core Recovery (REC):
The vessel mass inventory is increased by the ECC water injection and then the core recovers. The transient terminates when the entire core is quenched and the ECC water delivery by the DVI system alone exceeds the break flow and the vessel mass inventory increases.

5.0 Phenomena Identification and Ranking Table (PIRT)

A PIRT directly applicable to the Mitsubishi US-APWR considering the plant design features was developed for the current study. This PIRT is under review by independent reviewers external to MHI.

5.1 Definition of Rankings

The relative rankings were assigned using the following definitions:

H = The process is considered to have high importance. Accurate modeling of the process is considered to be crucial to the correct prediction of the transient. Models used to predict the process must be validated.

H* = The process is considered to have high importance. It is break size dependent so, in some cases, may be insignificant.

M = The process is considered to have medium importance. Modeling has to be made for appropriate process simulation,although the level of influence on the entire transient is expected to be lower than those ranked high (H) or (H*).

M* = The process is considered to have medium importance. It is break size dependent so, in some cases, may be insignificant.

L = The process is considered to have low importance. The phenomena need to be modeled in the code or explained in adequate detail in the methodology, although accuracy in modeling the process is not considered very influential to the whole transient.

L* = The process is considered to have low importance. For some break sizes, however, the phenomena should be modeled in the code.

N/A = The process is considered not to occur at all.

5.2 Discussions on Rankings

Table 1-1 lists small break LOCA phenomena and their relative rankings. This section discusses key categories in the PIRT, explains the way of ranking, and defines the phenomena considered as "process". Table 1-2 lists processes by respective components that are ranked high (H) at least once in the whole transient.

5.2.1. Fuel Rod

1. Stored Energy / Initial stored energy:

This is the total energy held in a fuel rod at the initial stage and throughout the transient. The process depends mainly on the gap conductance and the fuel pellet thermal conductivity. In a small break LOCA, the core is covered with coolant in early periods and reactor trips at an early stage. Large heat transfer between the fuel cladding and the coolant is maintained, and thus, there is a small temperature difference between the center of fuel rod and the coolant. Namely, most of the heat initially stored in the fuel rod is removed. Therefore, the process is ranked as low (L) through the whole transient.

2. Core Kinetics, Reactor Trip (Fission Power):
Reactor trips on "Reactor Trip Signal" generated due to "pressurizer pressure low" condition during "Blowdown period" in the US-APWR design as well as conventional PWRs. The effect of fission energy generated before the reactor trip is small because it corresponds to the steam generator heat removal. Fission rate is slightly affected by reactivity coefficient for moderator density and fuel temperature before fission terminates. Thus, the effect is ranked as medium (M) during the blowdown period and ranked as low (L) through the following periods.

3. Decay heat:
Decay heat is main resource of the local power of all the fuel rods after almost fission terminates. It affects the fluid conditions during the whole transient and the fuel temperature especially during core uncovery. Thus, the effect is ranked as medium (M) for the first two periods in which the core remains covered and as high (H) through the following periods.

4. Oxidation of Cladding:
This process is related to the metal-water reaction model and important only when the core is uncovered and the temperature of the fuel cladding exceeds around 1800F. This phenomenon is not applicable in the first two periods (blowdown, natural circulation) when the core is kept covered. In the loop seal clearance period the cladding temperature does not rise enough for the oxidation though core uncovery can occur, so the process is ranked as low (L).
For the following periods there is a possibility for the core to be uncovered and heated up till oxidation explicitly occurs in the large break case. The cladding temperature is not expected to be high enough to affect the cladding behavior. So, the process is ranked as medium (M) during the boil-off and core recovery periods.

5. Cladding Deformation (Creep/Burst):
This phenomenon is related to fuel rod parameters for determining the conditions for fuel cladding burst. This depends on pressure in a fuel rod, clad burst temperature, and clad bust strain. Because of low clad temperature, no burst is expected during the blowdown, natural circulation, and loop seal clearing periods. During the boil-off period, burst might occur if the core is uncovered and fuel cladding temperature rises to the burst temperature. Therefore, the fuel burst parameter is ranked as medium (M*) for the conditions when the core becomes uncovered.
(Symbol (*) indicates that the ranking is break size dependent.)

6. Gap conductance:
This parameter means conductivity of the fission gas in the gap between the fuel pellet and the cladding. The gap conductance affects the heat transfer from the pellet to the fuel cladding. Since the whole of the core remains covered during the blowdown period, the initial stored energy is effectively removed, resulting in the limited impact of gap conductance. Therefore this parameter is ranked as (L).

7. Local power:

This phenomenon includes axial and radial power shape which affects the initial linear power in the hot assembly and hot rod where the PCT occurs. The power distribution affects the core wide mixture level and the degree of steam superheat in the uncovered portion of the core. Also, peak linear heat generation rate affects the heat-up rate of the cladding resulting in magnitude of the PCT. These phenomena are considered to have low importance (L) in the periods of blowdown and natural circulation when the core has been submerged and cooled sufficiently. This is ranked as high (H*) for the periods of loop seal clearance when the core uncovery and the cladding temperature rise might occur depending on break size. This is ranked as high (H) for the periods of boil-off and core recovery when the core uncovery and the cladding temperature rise might occur.

5.2.2. Core

8. Departure from Nucleate Boiling (DNB):
Since a small break LOCA is a slow-going phenomenon and the local power is based on the decay heat because of the reactor trip in the early stage, the cladding temperature is mainly affected by the mixture level of the core. In other words heat-up of the cladding is initiated with uncovery of the fuel rod and DNB, which means a dryout with water, does not occur. Therefore DNB is not applicable.

9. Dryout
As stated above the cladding temperature behavior during a small break LOCA is mainly affected by the dryout of the fuel rod. So it is considered to be important how dryout occurs when mass inventory in the core is reduced. This phenomenon is not applicable in the first two periods (blowdown, natural circulation) when the core is submerged. For the following periods when the core uncovery might occur this phenomenon is ranked as high (H).

10. Post-Critical Heat Flux (CHF) Heat Transfer:
This phenomenon means heat transfer from the uncovered portion of the core. Information required for the heat transfer regime includes such regimes as inverted annular flow, dispersed flow, dispersed droplet film boiling and single-phase convection, together with the criteria (Minimum film boiling temperature T_{min} and void fraction) for setting the boundary between the regimes. For the blowdown and natural circulation periods when the core remains covered. The process is ranked as low (L) for these periods. For the loop seal clearance period and later on when the core might be uncovered and the cladding temperature might indicate higher, it is ranked as high (H).

11. Rewet (Heat transfer recovery):
This phenomenon means rewetting of the fuel cladding after the core uncovery. Since the core is submerged during the blowdown and the natural circulation periods, a low ranking (L) is assigned. In the loop seal clearance period and later on the core heat-up and the fuel rod rewetting might occur for small break LOCA. Thus, a high ranking (H) is assigned to these periods.

12. Entrainment/De-entrainment:
These phenomena mean entrainment in the axial direction at the quench front and de-entrainment in the bundle at higher elevations. In the boil-off and the core recovery periods, fuel rod could be heated up to a temperature enough to initiate these processes. The quenching process for a small break is under high pressure and cladding temperature falls in a short time following the core level recovery. Therefore, these phenomena are considered to be ranked as medium (M*) depending on break size.

13. 3-D Flow:
In the first two periods core is submerged and cooled sufficiently by the circulation flow of the primary loops. So the in-core circulation is considered to have a small impact. Therefore, this process is ranked as low (L) for these periods. In the loop seal clearance, boil-off, and recovery periods, the core mixture level during core uncovery can be affected by 3-D flow caused by the differences in the void fraction between assemblies. A medium ranking (M) is assigned to these periods.

14. Mixture level:
Interfacial friction between liquid phase and vapor phase in the core affects the two-phase mixture level. Flashing also affects the void fraction distribution, and thereby has an impact on the two-phase level. The mixture level eventually determines heat transfer at uncovered portion of the core, namely it exhibits an important influence. Therefore, the process is ranked as high (H) for the periods of loop seal clearance, boil off and core recovery period. During the blowdown and the natural circulation periods, the core is not uncovered, thus the process is ranked as not-applicable (N/A).

15. Flow resistance:
In a small break LOCA, the core flow rate is relatively small as compared to that in normal operation and large break LOCA because of the early pump coastdown and small break flow. So the frictional loss, form loss and acceleration are small and do not affect fluid behavior. This process is ranked as low (L) throughout the whole transient.

16. 3-D Power Distribution:
This parameter means power distribution in the radial and axial directions. This is considered to affect the void distribution in the core. During the blowdown and natural circulation periods the importance is considered to be low (L), since the core is submerged and the fuel temperature is kept slightly above liquid temperature. During the core uncovery the power distribution affects the mixture level, vapor superheat, and the cladding temperature rise. Thus, It is ranked as high (H) for the following periods.

17. Top Nozzle/Tie Plate CCFL:
This phenomenon means Counter-Current Flow Limitations (CCFL) that occur at the upper portion of the core in two-phase state. When the vessel mass is decreasing, liquid in the upper plenum is drained into the core region, which tends to makes core mixture level depletion delay. However, there is a possibility for the core generated steam to prevent the drainage from the upper plenum resulting in the early core uncovery depending on the break size. This phenomenon is considered to be important for a larger break size because the two-phase state and the uncovered core are achieved earlier. This process is ranked as low (L) for the first two periods when the vessel liquid is sufficient and ranked as medium (M*) for the following periods when the core uncovery might occur.

5.2.3. Neutron Reflector

18. Steam and Droplet Generation in Flow Holes:
Steam and droplet may be generated in the flow holes of the neutron reflector. This phenomenon is ranked as low (L) for all periods, because the heat release would be small at high temperature during small break LOCA.

19. Water Storage and Boiling in Back Region:

Water storage and boiling may occur in the back region of the neutron reflector. This phenomenon is ranked as low (L) for all periods, because the heat release would be small at high temperature during small break LOCA so that the boiling would be small and the condition is stagnant in this region.

20. Heat Transfer between Back Region and Core Barrel:
Heat transfer between the back region and the core barrel is ranked as low (L) for all periods, because the heat release would be small at high temperature during small break LOCA.

21. Core Bypass Flow:
The core bypass flow in the neutron reflector is ranked as low (L) for all periods, because this bypass flow rate is small compared to the core flow rate during small break LOCA.

5.2.4. Upper Head

22. Drainage to Core / Initial Fluid Temperature:
Initial fluid temperature of the upper head affects the timing when the upper head comes to a saturation state, and holds the system pressure. This factor is important in a large break LOCA with respect to stagnant core flow and reverse flow resulting from flashing. It might exhibit a similar impact in a small-break LOCA. The upper head temperature is determined by the influx (from downcomer and adjacent upper plenum to upper head) and discharge (flow from upper head center portion to upper plenum) in the normal state. The temperature affects the time as to when upper head has flashing. The upper head temperature depends how significant influx and discharge is achieved in the region, and takes a certain value between Tcold and Thot based on the thermo-hydraulics behavior of upper head/upper plenum. The factor is ranked as medium (M) for the blowdown period and for loop seal clearing period, when the water from upper plenum may occur depending on the initial temperature. It is ranked as low (L) for the succeeding periods when coolant is hardly remained.

23. Bypass Flow from Upper Head to Downcomer (Cold Leg):
There is a bypass flow from the upper head to the downcomer (cold leg). This process is ranked as low (L) for the blowdown and natural circulation periods, when the flow in the loop piping and core section is dominated by such flows as by RCP operation, SG secondary side cooling and break. The factor is ranked as medium (M) for the loop seal clearing period, when this flow path provide alternative steam flow paths from the upper plenum /upper head to the cold leg break opening which might alleviate the core mixture level depression. The importance of ranking gradually goes lower to a medium ranking (M*) for the boil-off and recovery periods for small break size.

24. Metal Heat Release:
This is included for completeness. Thus, it is ranked as Low importance (L) throughout the whole small break LOCA transient.

5.2.5. Upper Plenum

25. Mixture Level:
Since flashing in the upper plenum affects the void distribution and two-phase mixture level formation, flashing is considered to be a part of this process. The two-phase mixture level is ranked as medium (M) for the blowdown, natural circulation, and loop seal clearance periods, when upper plenum retains a substantial mass to form a significant two-phase mixture level and a source of water for the core. It is ranked as low (L) for boil-off and recovery periods,

when the water in the upper plenum has drained and there is little liquid in the upper plenum.

26. Draining to Core:
The flow from the upper plenum/hot leg to the core through the upper core plate, fuel assembly upper nozzle affects the amount of liquid below the core plate, namely, the amount of the coolant available to cool the hot assembly temperature. Since the overall core flow is upward during the blowdown and natural circulation periods and in-core void fraction is not predicted to show a substantial rise, the process is ranked as low (L) for these periods. During the period of loop seal clearing, flow is stratified and the steam generated in the core may limit the liquid draining through the upper plenum. The process is ranked as medium (M) for the loop seal period. During the boil-off and recovery periods, the upper plenum/hot leg is expected to be almost empty. The process is ranked as low (L) for these periods.

27. Entrainment/De-entrainment:
Droplets might transport from the upper plenum to the hot legs by the steam flow above the core mixture level. During the first two periods the core mixture level is generally above the hot leg bottom elevation and the steam flow rate from the reactor vessel to hot leg is low. Thus, low void fraction mixture flow is dominant in liquid transport to the hot legs. This process is ranked as low (L). In the later periods, the mixture level is below the hot legs and the natural circulation is broken so that some entrainment does not matter. For small break LOCA, the steam flow rate is low, as the core decay power is low, so, it is ranked as low (L) for these periods.

28. Bypass Flow / Hot Leg - Downcomer Gap:
There are leak paths between hot leg nozzles and the downcomer upper region throughout the entire operational modes. This gap-related leak occurs throughout all the periods. The direction of the leak depends on the pressure difference between the downcomer upper region and hot leg nozzle inner region. This process is ranked as low (L) for the blowdown and natural circulation periods, when the flow in the loop piping and core section is dominated by such flows as by RCP operation, SG secondary side cooling and break. The factor is ranked as medium (M) for the loop seal clearing period, when the above-described flow paths provide alternative steam flow paths from the upper plenum /hot legs to the cold leg break opening which might alleviate the core mixture level depression. The factor is ranked as medium (M*) for the boil-off and recovery periods for small break size.

29. Metal Heat Release:
This is included for completeness. Thus, it is ranked as Low importance (L) throughout the whole small break LOCA transient.

5.2.6. Hot Leg

30. Horizontal Stratification / Counter-flow:
This process of horizontal stratified flow at upper plenum and hot leg causes the vapor to slip from the upper plenum into the SGs. Flashing in the hot legs and upper plenum early in the transient contributes to the stratification. The process is ranked as medium (M) for the loop seal clearing period when the two-phase level is expected to lie as high as the hot legs. Horizontal stratification is ranked as low (L) in the boil-off, recovery periods, when two-phase level stays below the hot leg bottom elevation. For small break size, it is ranked as medium (M*) for boil-off period when the two-phase level may be higher than hot leg bottom elevation. It is ranked as low (L) for the blowdown and natural circulation period, when the amount of void is small in this region.

31. Entrainment/De-entrainment:
Liquid phase Entrainment/De-entrainment by vapor flow might occur in the hot leg. The vapor velocity and the liquid velocity is low because the pressurizer drains slowly to the hot leg. So, the entrainment is not considered to be significant. The process is ranked as low (L) throughout the all periods.

32. Metal Heat Release:
This is included for completeness. Thus, it is ranked as Low importance (L) throughout the whole small break LOCA transient.

5.2.7. Pressurizer and Surge Line

This PIRT assumes the break in the cold leg, and so is not appropriate to a transient of relief valve stuck open at the pressurizer.

33. Mixture Level:
In US-APWR design, reactor trip and SI trip might be triggered by only pressure. Therefore, the mixture level transient in the pressurizer is ranked as low (L) for the blowdown period. Flashing affects the level swell within the pressurizer and is incorporated in the level swell process. Since the pressurizer liquid flows out within a short time in most transients, it is ranked also as low (L) for the later periods.

34. Out-Surge by Depressurization:
The discharge rate from the surge line to the hot leg is slow, because the pressure difference between the pressurizer and the hot leg is small. Therefore no critical flow is expected to occur. Valves located on the top of the pressurizer are all closed, large vapor velocity into the pressurizer through the surge line is not expected, and thus there will be no liquid in-surge flow from the hot leg. The process is ranked as low (L) throughout the entire transient.

35. Metal Heat Release:
Energy stored in the pressurizer vessel wall including heat from the heaters within the pressurizer might affect the coolant outflow from the pressurizer. It is, however, ranked as low (L) throughout the transient because little metal heat is transferred to liquid/steam.

36. Location / Proximity to Break:
The discharge rate from the surge line to the hot leg is slow, because the pressure difference between the pressurizer and the hot leg is small. Therefore the effect of the location of the pressurizer is considered to be small for all periods are ranked low (L).

5.2.8. Steam Generator (SG)

37. Water Hold-up in SG Inlet Plenum:
Liquid holdup in the SG Inlet plenum including the inclined pipe affects the core water level during the loop seal period. The flow conditions in the SG Inlet plenum should be dominated by entrance effects due to the short distance and the change of flow directions. This process is ranked as (L) for the blowdown and natural circulation periods, when little or low void generation occurs and co-current flow still remains in the U-tubes. It is ranked as high (H) for the loop seal clearing period because of the potential for CCFL in this region and its impact on the core mixture level transient. Once the water is depleted in this region, this process is no

longer important and ranked as low (L).

38. Water Hold-up in U-Tube Uphill Side:
Liquid holdup and voiding on the primary side of the SG tubes affects the core water level during the loop seal period. Countercurrent flow in the U-tube leads to liquid holdup on the uphill side and voiding in the upper portion of the U-tube. This process is ranked as low (L) for the blowdown and natural circulation periods, when little or low void generation occurs and co-current flow still remains in the U-tubes. It is ranked as high (H) for the loop seal clearing period because of the potential for CCFL in the U-tubes and its impact on the core mixture level transient. Once the U-tubes are depleted of fluid, this process is no longer important and ranked as low (L).

39. Condensate Drainage to Inlet Plenum:
Condensate drainage to inlet plenum is related to water hold-up in SG inlet plenum. As a result, this phenomenon is ranked as high (H) for loop seal clearance period and is ranked as low (L) for other periods. For small break, the counter-current flow in boil-off period affects the core water level so that this phenomenon is ranked as (M*).

40. Primary side Heat Transfer:
In the blowdown and natural circulation periods, it is ranked as medium (M) in the view of the importance of heat transfer from primary system to secondary system. This is the main mechanism by which the core power is removed from the primary system so that it is important to evaluate this heat transfer. In the loop seal clearing period, this process is ranked as high (H) because it affects the condensation in the U-tubes. For the boil-off and recovery periods, it is ranked as low (L) because the heat transfer is from secondary to primary. For small break, the primary side pressure remains to be higher than the secondary side pressure during the boil-off period so primary side heat transfer is ranked as medium (M*).

41. Secondary side heat transfer (Water Level):
During the blowdown and the natural circulation periods, secondary side serves as heat sink so that secondary side heat transfer is ranked as medium (M). After loop seal clearing the direction of heat transfer is reversed from secondary to primary. Consequently, the process is ranked as medium (M). For the boil-off and recovery periods, it is ranked as low (L) because the heat transfer is from secondary to primary. For small break, the primary side pressure remain to be higher than the secondary side pressure during the boil-off period so secondary side heat transfer is ranked as medium (M*).

42. Metal heat release:
This is included for completeness. Thus, it is ranked as Low importance (L) throughout the whole small break LOCA transient.

43. Multi-U-tube Behavior:
There may be the difference in flow behaviors of U-tubes, which can be raised from the difference in the flow path length. The length of the U-tubes located in the peripheral region of the U-tube bundle is larger than that of the center region. Multi-U-tube effects can be expected when condensation occurs and the flow is in a two-phase condition. Therefore, the process is ranked as low (L) during the blowdown period. When the two-phase flow pressure drop in the U-tube changes according to its length, the ranking is a medium importance (M). This applies to the natural circulation and loop seal clearing periods, when condensation occurs in the SG. The ranking becomes low importance (L) in the boil-off and recovery periods when the U-tubes are essentially depleted of liquid.

44. Auxiliary Feed Water Flow:
When the secondary side serves as heat sink its heat transport efficiency is affected by the auxiliary feed water flow provided through the secondary water level. The direction of heat transfer is reversed after loop seal clearing (that is, from secondary to primary). The process is ranked as low (L) during the blowdown, when auxiliary feed water flow is not expected to occur. It is ranked as medium (M) during the natural circulation, loop seal clearance, and boil-off periods. It is ranked as low (L) during the recovery period, when the core is cooled down by the ECC water injected to the RCS

5.2.9. Crossover Leg

45. Water Level in SG Outlet Piping:
The water level in SG outlet piping is ranked low (L) for the blowdown and natural circulation periods since it does not affect the core water level before the loop seal formation. This process affects the initiation of the core water level depletion for the loop seal clearing period. This process is ranked as high (H) for this period, because the water inventory in the SG outlet piping is the initial condition for the loop seal piping. During the boil-off period and recovery period, this process is ranked as low (L) because this water level is empty.

46. Loop Seal Formation and Clearance (Entrainment/Flow regime/Interfacial drag/Flow resistance):
Loop seal formation is the water seal in the pump suction pipe and prior to the loop seal clearance, the core collapsed level can reduce as a result of static water head balancing within the RCS. More specifically the core level depletion is affected by the water head at the pump suction and the uphill side of SG. After the loop seal clearance, the water level in the reactor vessel recovers to the cold leg elevation as the steam venting dissolves the water head imbalance throughout the RCS. If the mixture core level drops to the core top and core uncovery initiates, the cladding temperature in the upper part of the core may begin to rise rapidly. Loop seal formation and clearance process is ranked as high (H) in the loop seal clearing period. It is ranked as medium (M) in the boil-off period when a stagnant layer of liquid may rest at the bottom of the horizontal section and affect the core water level. This process is ranked as low (L) in the recovery period when the core recovery is affected little by the water in the pump suction. This process is ranked as low (L) during the blowdown period and the natural circulation period.

47. Metal Heat Release:
This is included for completeness. Thus, it is ranked as Low importance (L) throughout the whole small break LOCA transient.

5.2.10. RCP

48. Coastdown Performance:
The coastdown performance the RCPs affects the flow during the period between pump trip and termination of coastdown. For a medium break, this process is ranked as medium (M) because the RCP coastdown occurs during the blowdown period. Rankings for the later periods are not-applicable (N/A) because the RCPs serve only as a resistance after the termination of the coastdown.

49. Two-phase Flow Performance:

The two-phase flow performance of the RCPs affects the flow while the pump suction conditions are two-phase. For the blowdown period, this process is ranked as low (L) because the two-phase flow duration is short. During the natural circulation and loop seal clearance periods, it is ranked as low (L) because though pump trip is expected to be triggered relatively early in the transient, the natural circulation flow is a balance between the gravity and two-phase head differences and the loop resistance. During the boil-off and recovery period, it is ranked as not-applicable (N/A) because pump trip is expected to occur before these periods.

50. Reversal Flow of ECC Water:
There may be reversal flow of ECC water to the RCP suction pipes. Then countercurrent flow limitation might occur associated with liquid flow back through the RCP caused by vapor flowing towards the break. In the US-APWR design, the high pressure SI pumps directly to the downcomer inject ECC water. Therefore, this process is ranked as not-applicable (N/A) for these periods. For the recovery period, when injection by the accumulators is expected to occur at the cold legs, a low (L) ranking is assigned to this process.

51. Metal heat release:
This is included for completeness. Thus, it is ranked as Low importance (L) throughout the whole small break LOCA transient.

5.2.11. Cold Leg

52. Stratification Flow:
The stratification flow in the broken cold leg affects the break flow behavior. This process is ranked as low (L) during the blowdown and natural circulation periods because the cold leg remains nearly filled with water. During the loop seal clearing, boil-off period, and recovery periods, when the two-phase level decreases in the cold leg and, as a result, break is uncovered, it is ranked as medium (M*) depending on break size.

53. Condensation by ACC water:
The condensation of steam by ACC water injection in the cold leg is ranked as not-applicable (N/A) during the first four periods before the ACC injection. For a medium size break case, when the accumulator water injection to the cold legs is expected to occur, this process is ranked medium (M*).

54. Non-condensable Gas Effect:
The nitrogen gas is not injected into the primary system until the accumulator injection almost terminates. Therefore, this process is ranked as non-applicable (N/A) for the blowdown period, natural circulation, loop seal clearance and boil-off periods. It is ranked as low (L*) for the recovery period, since the gas effect will depend on the break size and the gas may not matter if the core is fully quenched before the gas comes out.

55. Metal heat release:
This is included for completeness. Thus, it is ranked as Low importance (L) throughout the whole small break LOCA transient.

5.2.12. Accumulator:

56. Large Flow Injection / Flow Resistance:
The flowrate discharged from the accumulators affects the core water level. Since the

accumulators do not start liquid injection until the recovery period, this process is ranked as not-applicable (N/A) for the first four periods. During the recovery period, a medium (M*) is assigned for a medium size break case, when core recovery is expected to occur after initiation of the accumulator water injection.

57. Small Flow Injection / Flow Resistance:
The flowrate discharged from the accumulators affects the core water level. Since the accumulators do not start liquid injection until the recovery period, this process is ranked as not-applicable (N/A) for the first four periods. During the recovery period, a low ranking (L) is assigned for a medium size break case, when core recovery is expected to occur after initiation of the accumulator water injection. This process is ranked as (L) because the effect is considered to be small compared to the large flow injection.

58. Interfacial Heat Transfer:
Small LOCA transients last over a considerably longer duration, heat transfer between a nitrogen gas and subcooled water may occur in the accumulators. Since the accumulator water injection is not initiated until the recovery period, this process is ranked as not-applicable (N/A) for the first four periods, and as low (L) for the recovery period when the accumulator water injection rate may be affected a little.

59. Metal heat release:
Small LOCA transients last over a considerably longer duration, heat transfer between a nitrogen gas and accumulator tank wall occur. Since accumulator water injection is not initiated until the recovery period, this process is ranked as not-applicable (N/A) for the first four periods, and as low (L) for the recovery period when the accumulator water injection rate may be affected a little.

60. Injection of Nitrogen gas Effects:
Non-condensable gas effect might affect when accumulator nitrogen cover gas is discharged into the RCS. In small LOCAs accumulator water injection is not initiated until the recovery period. This process is ranked as not-applicable (N/A) for the first four periods. This process is ranked as (L*) for the recovery period of medium beak size case when the accumulators are expected to empty, because the injection would be small for these break sizes.

1-6-12 Downcomer Region / Lower Plenum

61. Water Head Decrease by Void Generation:
In the small LOCA transient, the downcomer two-phase mixture water head is the driving force to feed coolant into the core, and is reduced by increase of the void fraction in the downcomer. This process is ranked as low (L) for the blowdown and natural circulation periods, when the pressure is high, thus no flashing occurs in the downcomer, and the steam flowrate is small in the RCS. This process is ranked as medium (M) for the loop seal clearance period because the steam flowrate is expected to increase. During the boil-off and recovery periods, this process is ranked as medium (M*) for medium size breaks, because the RCS pressure may become low to the point at which flashing occurs in the downcomer.

62. Mixture Level:
The downcomer two-phase mixture water head is the driving force to feed coolant into the core, and is reduced by the decrease of the downcomer mass inventory. During the blowdown period and natural circulation periods, this process is ranked as medium (M) as the downcomer mixture level remains around the cold leg elevation. For the later periods, this

process is ranked as high (H) since the downcomer mixture level affects the core mixture level and the break flow.

63. Metal heat release:
The metal heat from the downcomer wall releases to fluid in the downcomer. A low (L) ranking is assigned for the first four periods because in small break LOCAs the RCS depressurization is slow, most of the metal structures are covered by fluid, and heat release is gradual. During the recovery period, the RCS pressure may become low to the point at which flashing occurs in the downcomer. Therefore, this process is ranked as medium (M).

64. ECC Water / mixing:
The mixing of safety pump injection and accumulator water occurs with the remaining fluid in the downcomer. This process is ranked as not-applicable (N/A) for the blowdown period because the safety pump injection flow does not initiate. For the natural circulation, loop seal clearance, and boil-off periods, a low ranking (L) is assigned because the safety pump injection flow is expected to inject into the coolant in the downcomer. For the recovery period, this process is ranked as medium (M) since the accumulator water may be injected.

65. 3-D Flow:
Multidimensional flow which may occur in the downcomer. This may be important for intermediate size break LOCAs in which a non-uniform mixture level is formed around the downcomer by partial depletion of liquid during the blowdown period. This process is ranked as between low (L) and medium (M*) for the blowdown period because the effect of 3-D flow might affect the core cooling. It is ranked as medium (M) for the recovery period because of the injection of accumulators. For the other three periods, this process is ranked as low (L).

66. DVI / SI Water / Flowrate:
Subcooled water flowrate would be injected directly into the downcomer by the safety pumps. This process is ranked as not-applicable (N/A) for the blowdown period because safety pump injection is not initiated. For the natural circulation, a medium ranking (M) is assigned because the effect of safety pump injection affects the termination of the natural circulation. A high ranking (H) is assigned for the later periods because the DVI water affects the core water level depletion and recovery.

67. DVI / SI Water / Condensation:
Condensation is caused by subcooled water injected directly into the downcomer by the safety pumps. This process is ranked as not-applicable (N/A) for the blowdown period because safety pump injection is not initiated. For the later periods, a medium ranking (M) is assigned because of the initiation of safety injection and void increase in the downcomer. Since the DVI nozzles are located below the centerline elevation of the cold leg nozzles, subcooled water is injected below the downcomer water level, and thus a large interfacial area for condensation is not expected to generate.

68. DVI / SI Water / Injection Temperature:
Temperature of the safety pump injection varies after a break occurs. The US-APWR design employs the Refueling Water Storage Pit (RWSP) installed inside the containment vessel and eliminates the switchover operation of safety pump injection water resources following LOCAs. This process is ranked as not-applicable (N/A) for the blowdown period because safety pump injection is not initiated. A medium ranking (M) is assigned for the later periods because the safety injection water temperature rise affects the core cooling behavior.

5.2.13. Break

69. Critical Flow:
Critical flow affects the break flowrate during all the periods for small LOCA break transients. Therefore, this process is ranked as high (H) for all the periods.

70. Break Flow Enthalpy:
The break flow quality and enthalpy depend on the broken cold leg condition. This process is ranked as medium (M) for all periods because the break flow mass and enthalpy determines the system mass inventory and affects the RCS pressure.

Table-1 PIRT for Small Break LOCA (1/2)

Location	Process / Phenomena	Small Break LOCA				
		Blowdown	Natural Circulation	Loop Seal Clearance	Boil-off	Recovery
FUEL ROD						
1	Stored Energy / Initial Stored Energy	L	L	L	L	L
2	Core kinetics, Reactor trip (fission power)	M	L	L	L	L
3	Decay Heat	M	M	H	H	H
4	Oxidation of Cladding	N/A	N/A	L	M	M
5	Clad Deformation (Creep/Burst)	N/A	N/A	L	M*	M*
6	Gap Conductance	L	L	L	L	L
7	Local Power	L	L	H*	H	H
CORE						
8	CHF (DNB)	N/A	N/A	N/A	N/A	N/A
9	Dryout	N/A	N/A	H	H	H
10	Post-CHF Heat Transfer	N/A	N/A	H	H	H
11	Rewet (Heat Transfer Recovery)	N/A	N/A	H	H	H
12	Entrainment / De-entrainment	L	L	L	L	M*
13	3-D Flow	L	L	M	M	M
14	Mixture Level	N/A	N/A	H	H	H
15	Flow Resistance	L	L	L	L	L
16	3-D Power Distribution	L	L	H	H	H
17	Top Nozzle / Tie Plate CCFL	L	L	M*	M*	M*
Neutron Reflector						
18	Steam and Droplet Generation in Flow Holes	L	L	L	L	L
19	Water Storage and Boiling in Back Region	L	L	L	L	L
20	Heat Transfer between Back Region and Core Barrel	L	L	L	L	L
21	Core Bypass Flow	L	L	L	L	L
Upper Head						
22	Drainage to Core / Initial Fluid Temperature	M	L	M	L	L
23	Bypass Flow between Upper Head and Downcomer(Cold Leg)	L	L	M	M*	M*
24	Metal Heat Release	L	L	L	L	L
Upper Plenum						
25	Mixture Level	M	M	M	L	L
26	Drainage to Core	L	L	M	L	L
27	Entrainment / De-entrainment	L	L	L	L	L
28	Bypass Flow / Hot Leg - Downcomer Gap	L	L	M	M*	M*
29	Metal Heat Release	L	L	L	L	L
Hot leg						
30	Stratifiled Flow / Counter-flow	L	L	M	M*	L
31	Entrainment / De-entrainment	L	L	L	L	L
32	Metal Heat Release	L	L	L	L	L
Pressurizer and Surge Line						
33	Mixture Level	L	L	L	L	L
34	Out-Surge by Depressurizarion	L	L	L	L	L
35	Metal Heat Release / Heater	L	L	L	L	L
36	Proximity to the Break	L	L	L	L	L

* means that the ranking is "break size dependent."

Table-1 PIRT for Small Break LOCA (2/2)

Location / Process / Phenomena		Small Break LOCA: Blowdown	Natural Circulation	Loop Seal Clearance	Boil-off	Recovery
Steam Generator						
37	Water Hold-Up in SG Plenum	L	L	H	L	L
38	Water Hold-Up in U-Tube Uphill Side	L	L	H	L	L
39	Condensate drainage to inlet plenum	L	L	H	M*	L
40	Primary Side Heat Transfer	M	M	H	M*	L
41	Secondary Side Heat Transfer (Water Level)	M	M	M	M*	L
42	Metal Heat Release	L	L	L	L	L
43	Multi-Tube Behavior	L	M	M	L	L
44	AFW	L	M	M	M	L
Crossover Leg						
45	Water level in SG outlet piping	L	L	H	L	L
46	Loop Seal formation and Clearance (Entrainment/Flow regime/Interfacial drag/Flow resistance)	L	L	H	M	L
47	Metal Heat Release	L	L	L	L	L
Reactor Coolant Pump						
48	Coastdown by Performance	M*	N/A	N/A	N/A	N/A
49	Two-Phase Flow Performance	L	L	L	N/A	N/A
50	Reveral Flow of ECC Water	N/A	N/A	N/A	N/A	L
51	Metal Heat Release	L	L	L	L	L
Cold Leg						
52	Stratifiled Flow	L	L	M*	M*	M*
53	Steam Condensation by ACC Water	N/A	N/A	N/A	N/A	M*
54	Injection of N2 Gas	N/A	N/A	N/A	N/A	L*
55	Metal Heat Release	L	L	L	L	L
Accumulator						
56	Large Flow Injection/Flow Resistance	N/A	N/A	N/A	N/A	M*
57	Small Flow Injection/Flow Resistance	N/A	N/A	N/A	N/A	L*
58	Interfacial Heat Transfer	N/A	N/A	N/A	N/A	L
59	Metal Heat Release	N/A	N/A	N/A	N/A	L
60	Injection of N2 Gas Effect	N/A	N/A	N/A	N/A	L*
Downcomer/Lower Plenum						
61	Water Head Decrease by Void Generation	L	L	M	M*	M*
62	Mixture Level	M	M	H	H	H
63	Metal Heat Release	L	L	L	L	M
64	ECCS Water / Mixing	N/A	L	L	L	M
65	3-D Flow	L-M*	L	L	L	M
66	DVI/SI Water / Flowrate	N/A	M	H	H	H
67	DVI/SI Water / Condensation	N/A	M	M	M	M
68	DVI/SI Water / Injection Temperature	N/A	M	M	M	M
Break						
69	Critical Flow	H	H	H	H	H
70	Break Flow Enthalpy	M	M	M	M	M

* means that the ranking is "break size dependent."

Table-2 PIRT for Small Break LOCA (High rank)

Location	Process / Phenomena	Small Break LOCA				
		Blowdown	Natural Circulation	Loop Seal Clearance	Boil-off	Recovery
FUEL ROD						
3	Decay Heat	M	M	H	H	H
7	Local Power	L	L	H*	H	H
CORE						
9	Dryout	N/A	N/A	H	H	H
10	Post-CHF Heat Transfer	N/A	N/A	H	H	H
11	Rewet (Heat Transfer Recovery)	N/A	N/A	H	H	H
14	Mixture Level	N/A	N/A	H	H	H
16	3-D Power Distribution	L	L	H	H	H
Steam Generator						
37	Water Hold-Up in SG Plenum	L	L	H	L	L
38	Water Hold-Up in U-Tube Uphill Side	L	L	H	L	L
39	Condensate drainage to inlet plenum	L	L	H	M*	L
40	Primary Side Heat Transfer	M	M	H	M*	L
Crossover Leg						
45	Water level in SG outlet piping	L	L	H	L	L
46	Loop Seal formation and Clearance (Entrainment/Flow regime/Interfacial drag/Flow resistance)	L	L	H	M	L
Downcomer/Lower Plenum						
62	Mixture Level	M	M	H	H	H
66	DVI/SI Water / Flowrate	N/A	M	H	H	H
Break						
69	Critical Flow	H	H	H	H	H

* means that the ranking is "break size dependent."